Characterization of Thin Film Microstrip Lines on Polyimide

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***Abstract*—This paper presents an in depth characterization of thin film microstrip (TFMS) lines fabricated on Dupont PI-2611 polyimide. Measured attenuation and effective dielectric constant is presented for TFMS lines with thicknesses from 2.45–7.4 μm and line widths from 5–34.4 μm over the frequency range of 1–110 GHz. The attenuation is separated into conductor and dielectric losses to determine the loss tangent of Dupont PI-2611 polyimide over the microwave frequency range. In addition, the measured characteristics are compared to closed form equations for α and $\epsilon_{\rm eff}$ from the literature. Based on the comparisons, recommendations for the best closed form design equations for TFMS are made.**

***Index Terms*— Microstrip, microwave, multilayer, polyimide, transmission lines.**

I. Introduction

Wireless communications, personal communications, direct broadcast television, local multipoint distribution systems (LMDS), automatic highway toll systems, and many other rapidly growing industries are relying on small, low cost RF and microwave components. This has led to the increased use of multichip modules (MCM's) that incorporate analog and digital circuits within a single package. Although conventional microwave transmission lines and control lines on ceramic substrates with wirebonds can be used in the MCM's, this does not lead to either low cost or smaller components. In addition, the parasitic reactances associated with conventional transmission lines and wire bonds severely limits the bandwidth of the circuits. Instead, a preferred approach is to integrate all of the circuits together onto a single carrier using thin film transmission lines and small via holes. This increases the packing density within the MCM and decreases the parasitic reactances compared to conventional circuits.

Except for a difference in scale, thin film microstrip (TFMS) appears to be similar to conventional microstrip, but its electrical characteristics are very different. TFMS uses thin dielectric layers deposited on top of a ground plane which has been deposited onto a carrier substrate such as GaAs, Si, or Alumina as shown in Fig. 1. By definition, the dielectric layers are thin with the substrate height, H, of TFMS between 1 and 25 μm, compared to conventional microstrip substrate thicknesses between 100 and 500 μm. Although, in principal, any good insulator could be used for the dielectric layers, typically polyimide [1], [2], BCB [3], or SiON [4], [5] is used because of compatibility with monolithic microwave integrated circuit

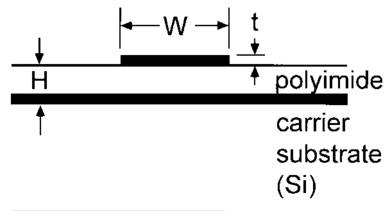

Fig. 1. Schematic of thin film microstrip (TFMS).

(MMIC) processing steps, low cost, and ease of use. These materials have relative dielectric constants of approximately 3, 3, and 5, respectively, compared to 9.9, 11.9, and 12.85 for Alumina, Si, and GaAs, respectively. In addition, since TFMS is often used for multilayer interconnects and miniature MMIC's that require planar surfaces for lithography steps, the metal thickness of the strip, t, and the ground plane must be small. Typically, $t \leq 1.5$ μm which is less than half the plated line thickness used for conventional microstrip circuits. Lastly, the line width, W, required for the standard range of characteristic impedances is between 5 and 35 μm.

The small dimensions which describe TFMS offer several advantages to the microwave circuit designer: the thin substrate is easily etched to form very small via holes; the small line widths lead to denser circuits; and the use of ground planes between dielectric layers permit novel circuit layouts that minimize circuit size. In addition, the low relative dielectric constant results in a higher propagation velocity which is necessary for high speed digital circuits. These advantages have been exploited for microwave multilayer interconnect technology and miniaturized MMIC's [1], [4], [5].

Standard microstrip has been fully characterized, both experimentally [6]–[9] and theoretically [10], yielding accurate design equations to predict the characteristic impedance and phase velocity [11]–[13]. In addition, closed form equations to predict the dielectric and conductor losses of conventional microstrip have been presented [14]–[18]. For TFMS, measured attenuation has been presented for several geometries up to 25 GHz [2], [5] with practically no measured dispersion results available. Although not specifically derived for TFMS, several papers have presented closed form equations to predict the conductor loss of microstrip lines with thin metal strips [5], [19]–[21].

This paper presents for the first time a comprehensive experimental characterization of TFMS fabricated on polyimide with a wide range of microstrip geometries over the frequency range of 1–110 GHz. From these results, the dielectric loss tangent of Dupont PI-2611 polyimide over the microwave

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spectrum is determined. In addition, a comparison of the measured attenuation and effective dielectric constant, $\epsilon_{\rm eff}$, to the values predicted by design equations is presented to establish the best design equations for TFMS and the error that can be expected in using each of the design equations.

II. Experiment

For the characterization of TFMS, four sets of test structures, each with a different polyimide thickness, were fabricated in parallel. Each set of test structures contains TFMS lines of seven different strip widths. A ground plane consisting of a 200 Å Ti adhesion layer and 2.5 μm of Au was evaporated onto a standard 4–12 Ω-cm Si wafer which served as a carrier. Since the ground plane isolates the microstrip from the Si, any flat material could have been used as a carrier. This was followed by spinning on Dupont adhesion promoter and Dupont PI-2611 polyimide which has a permittivity of 3.12 [22] measured at 1 MHz and a loss tangent of 0.002 [23] measured at 1 kHz. The spin speed was varied between 5000 and 2000 rpm to yield polyimide thicknesses between 2.45 and 7.4 μm in a single layer. After drying the polyimide, it was cured at 350 °C for 60 min in an N_2 atmosphere. Next, spin on glass (Allied 512) was applied over the polyimide to serve as a mask for the 20% CF_4 in O_2 reactive ion etching of the via holes. Finally, a lift off process was used to fill the via holes and define the probe pads and microstrip lines in a single step; 200 Å of Ti and 1.3 μm of Au is used. After fabrication, a DEKTAK surface profile was used to measure the polyimide and metal strip thickness. Both, the DEKTAK and SEM analysis show that the surface roughness is low enough that it can be neglected in the analysis.

The microwave characterization of the TFMS is performed over the frequency range of 1–40, 50–75, and 75–110 GHz using an HP 8510C vector network analyzer (VNA) and two sets of millimeter-wave test modules. A total of 403 frequency points is measured over the 1–110 GHz. The separation of the frequency band into sub-bands is required because of limitations with the HP8510C. In addition to lengthening the measurement time, this introduces discontinuities in the data at 40/50 and 75 GHz due to differences in the test modules. Transitions from the 2.4 mm coax and the rectangular waveguide test ports of the 1–40 GHz HP 8510C and the millimeter-wave modules respectively to the TFMS is made via GGB Industry microwave probes with a 150 μm pitch. The probe pads are the same for all of the TFMS circuits; they are comprised of a linear taper to transition the center contact to the desired TFMS width and a pair of via holes on either side of the center conductor to permit the two outer probe contacts to make electrical connections to the TFMS ground plane. Temperature of the laboratory during the measurements is 20 °C.

To extract the attenuation and effective dielectric constant of the TFMS, a thru-reflect-line (TRL) calibration routine, MULTICAL by NIST, [24] is used with the calibration standards being the TFMS lines. Each set of standards consists of a THRU line of 5000 μm length, four DELAY lines of 6800, 7400, 9800, and 15 000 μm length, and an open circuit terminated TFMS. The advantage of this measurement method is that it extracts the attenuation and effective dielectric constant from the measured differences in the S-parameters between the THRU and DELAY lines at the same time that the system is calibrated which minimizes the number of probe contacts and the resulting errors. In addition, since all five lines are used at each frequency point in a weighted average, the measured line characteristics are more accurate than if a single measurement is used. To further improve the accuracy of the measurements, the probe pads are designed to assure probe placement repeatability to within ± 15 μm, although it was determined that a probe placement repeatability of ± 5 μm is accomplished. Assuming the worst case error of ± 15 μm in probe placement, the associated error in attenuation and phase at 110 GHz is approximately 0.025 dB and 6°, respectively. Finally, each set of data reported in this paper is an average of at least three measurements made at different points across the wafer to reduce the effects of processing variations across the wafer and to minimize random errors. The typical error between these three measurements over the 1–40 GHz band is 4%.

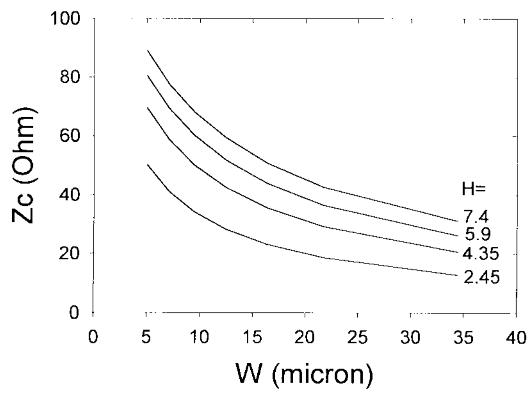

Fig. 2. Calculated characteristic impedance of TFMS lines.

III. Measured Propagation Characteristics

TFMS lines were characterized for polyimide thicknesses of 2.45, 4.35, 5.90, and 7.40 μm and line widths of 5.0, 7.1, 9.5, 12.5, 16.4, 21.7, and 34.4 μm. Employing standard microstrip design equations [11], these geometries result in characteristic impedances in the range of 12–89 Ω as shown in Fig. 2.

The measured attenuation and effective dielectric constant for each set of TFMS lines is shown in Figs. 3 and 4, respectively. At 40 and 75 GHz, discontinuities in the data resulted from the need to reconfigure the network analyzer to cover different waveguide bands. It is first noted that TFMS is a lossy transmission line compared to conventional microstrip lines on 100 μm thick GaAs with a metal strip thickness of 3 μm [6]. For the 2.45 μm thick polyimide TFMS, the attenuation is approximately a factor of ten higher than microstrip lines on GaAs with the same characteristic impedance, and the attenuation of TFMS with 7.4 μm thick polyimide is a factor of four higher. The variation in attenuation with strip width, W, for a specific polyimide thickness is less than ± 0.5 dB at 40 GHz indicating that a wide range of characteristic impedances can be achieved without a large penalty in loss.

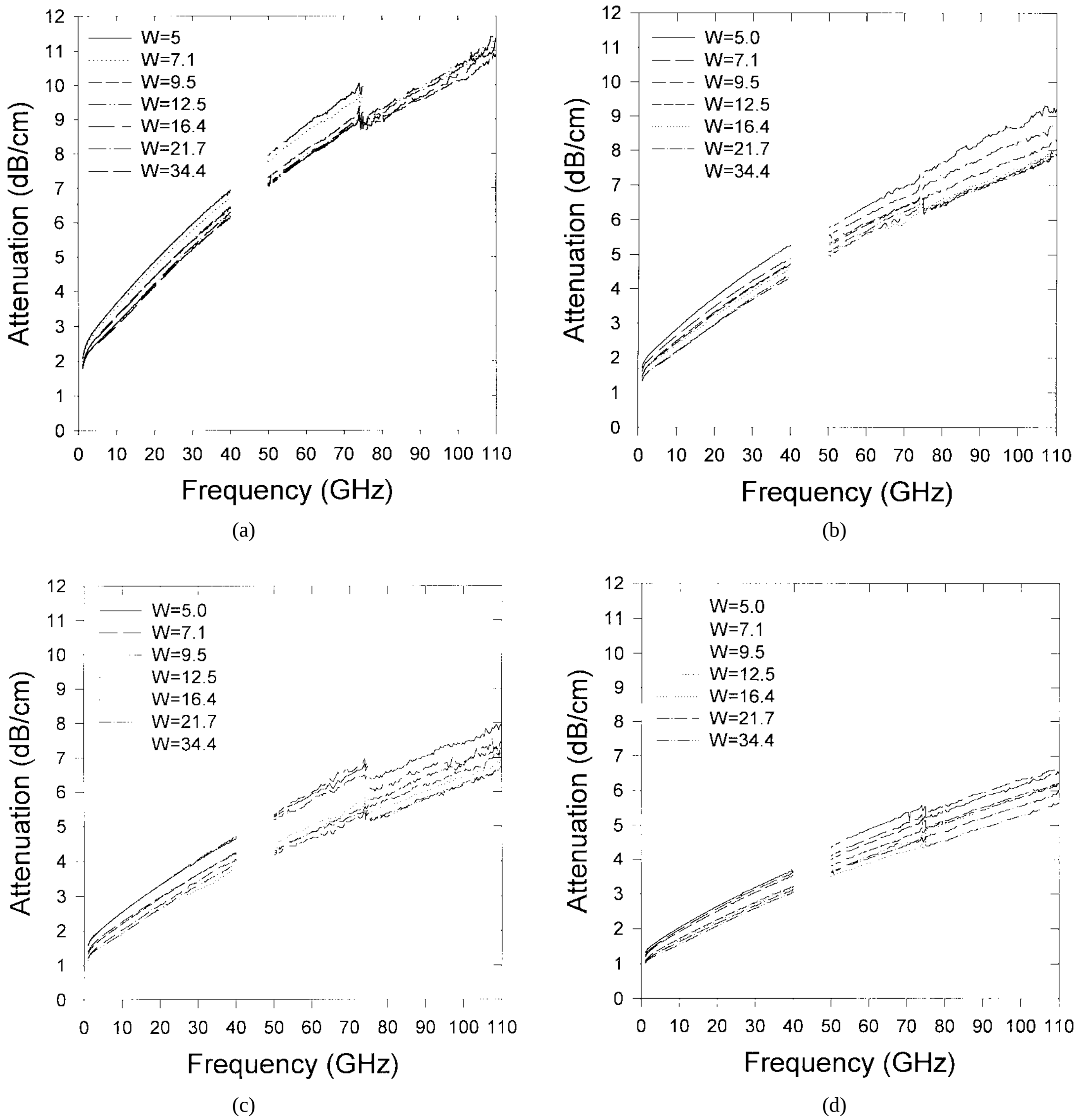

Fig. 3. Measured attenuation of TFMS lines with polyimide thickness of (a) 2.45 μm, (b) 4.35 μm, (c) 5.90 μm, and (d) 7.40 μm.

The different loss mechanisms of the TFMS can be quantified by separating the attenuation into its conductor and dielectric loss components. Conductor loss for thick metal strips and ground planes, $t/\delta \gg 1$ where $\delta = 1/\sqrt{\pi\mu_o\sigma f}$ is the skin depth and σ is the conductivity of the metal, is proportional to the square root of frequency [17]. Dielectric loss in polyimide is dominated by the polarization current which results in a dielectric attenuation of

$$\alpha_d = \frac{27.3}{c}\frac{\epsilon_r'}{\sqrt{\epsilon_{re}}}\frac{\epsilon_{re}-1}{\epsilon_r'-1} f \tan\delta \quad \text{(dB/unit length)} \tag{1}$$

where c is the velocity of light, $\epsilon = \epsilon' - j\epsilon''$ is the complex permittivity, $\epsilon_r' = \epsilon'/\epsilon_o, f$ is the frequency, $\tan\delta = \epsilon''/\epsilon'$ is the loss tangent, and ϵ_{re} is the effective permittivity of the microstrip line at zero frequency [17]. Thus α_d is linearly proportional to frequency and the measured attenuation should be fit by

$$\frac{\text{insertion loss in dB}}{\text{unit length}} = a\sqrt{f} + bf. \tag{2}$$

Because the polyimide is thin, radiation loss is neglected in (2).

The conductor loss term, a, and the dielectric loss term, b, are determined by a least squares fit to the measured data for each line. Fig. 5 shows the conductor loss term for each line. It is seen that the conductor loss decreases as the polyimide thickness increases and as the line width increases, and the decrease in attenuation with increasing line width saturates for wide lines. It is also found that for low frequency ($f < 5$ GHz) the attenuation does not fit the square root of frequency dependence. A modified skin depth has been proposed by Hiraoka [5]

$$\delta' = \delta(1 - e^{-t/\delta}) \tag{3}$$

that extends the skin depth to the frequency range where t/δ is not large. By expanding the exponential term, it can be shown that δ' varies between t and δ as the frequency increases. Thus, the power of the frequency dependence of the conductor loss increases from 0–0.5 as the frequency increases. Although not predicted by the modified skin depth, the inflection point where the measured attenuation changes to a square root dependence is found to be dependent on the line width.

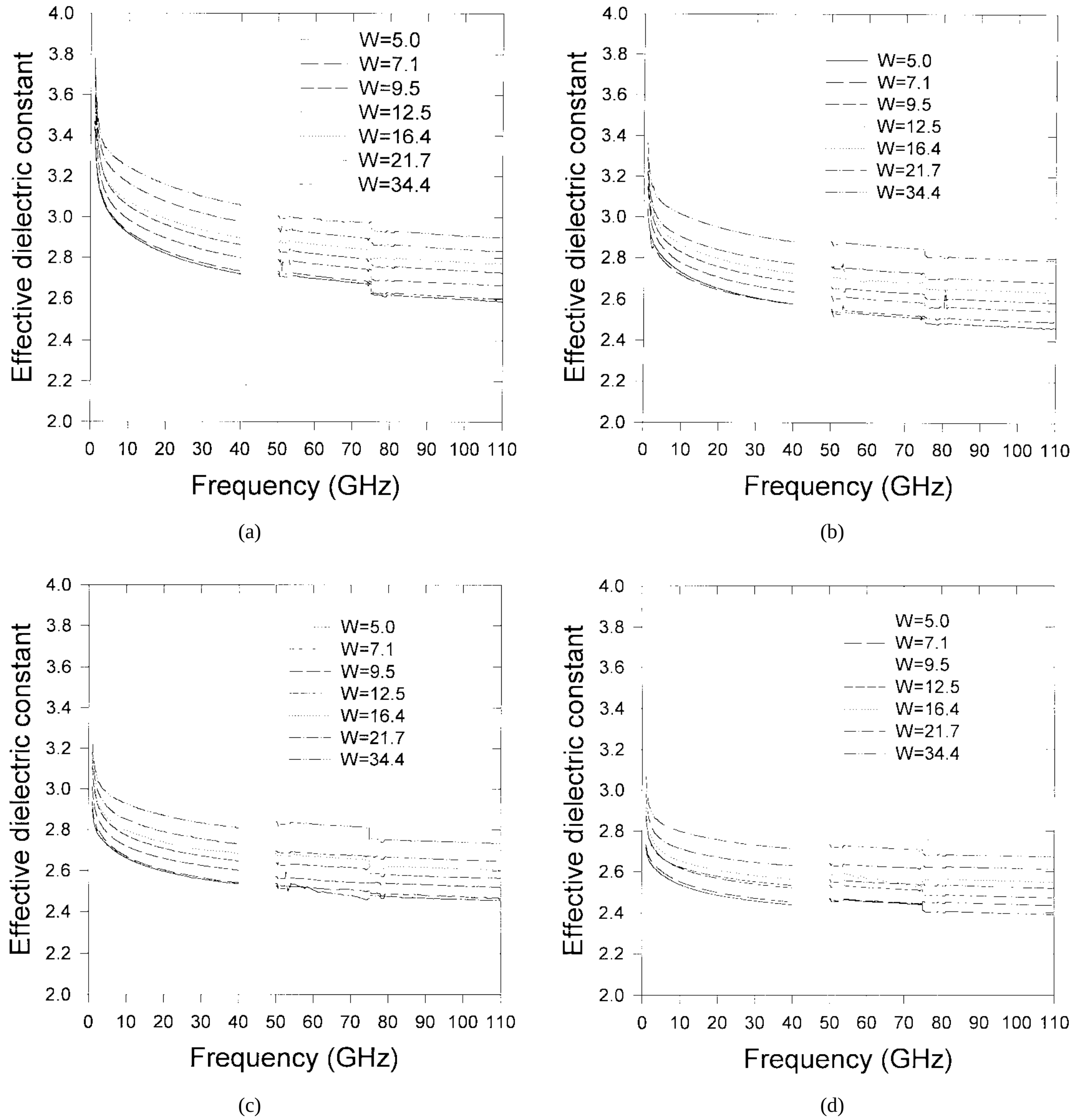

Fig. 4. Measured effective dielectric constant of TFMS lines with polyimide thickness of (a) 2.45 μm, (b) 4.35 μm, (c) 5.90 μm, and (d) 7.40 μm.

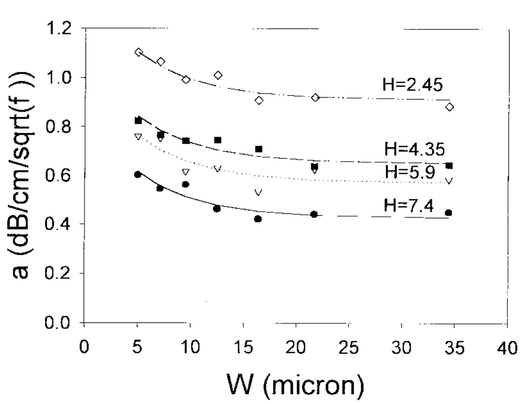

Fig. 5. Conductor loss term, a, for TFMS deembedded from measured attenuation.

After the dielectric loss term, b, is determined, the loss tangent of the polyimide over the microwave spectrum can be determined from (1) and the measured effective dielectric constant (Note: Instead of using the zero frequency dielectric constant, the lowest measured permittivity value was used. This will be discussed further below). The average loss tangent from all 28 sets of TFMS lines is found to be 0.006. This value is higher than the published value of 0.002 at 1 kHz [23] which is expected since the loss tangent typically increases with frequency. Also, the measured loss tangent of the PI-2611 polyimide found here is in the same range as that measured for other low dielectric constant materials [3]. Unfortunately, there is substantial error in the determination of the loss tangent using this method that results in a large spread in the results. Some of the uncertainties arise from: the correct frequency dependence of the conductor loss at low frequency is not accounted for in (2); the dielectric loss is very low compared to the conductor loss; determination of ϵ_{re} is difficult for lossy transmission lines; and the dielectric loss is more dependent on the uniformity and quality of the polyimide across the wafer.

The measured effective dielectric constant shown in Fig. 4 has a strong slow wave effect which is due to the high

TABLE I
AVERAGE OF $|\alpha_{\text{meas}}(f) - \alpha_{\text{calc}}(f)|$ IN dB/cm ACROSS THE FREQUENCY BAND OF 1–110 GHz FOR THE CLOSED FORM EQUATIONS FROM [5], [14], [15], [17]–[19], [21], AND [22]

H (μm)	W (μm)	[14]	[15]	[22]	[17]	[19]	[18]	[21]	[5]
2.45	5.0	1.29	3.79	1.37	4.88	1.65	1.51	3.49	1.74
2.45	7.1	1.54	2.48	1.65	5.11	1.07	1.80	3.32	2.00
2.45	9.5	2.00	1.92	2.12	5.75	0.92	2.26	3.56	2.49
2.45	12.5	2.06	1.19	2.19	6.10	0.47	2.26	3.44	2.56
2.45	16.4	2.40	0.86	2.52	6.78	0.33	2.52	3.65	2.91
2.45	21.7	2.50	0.39	2.61	7.16	0.16	2.55	3.64	3.03
2.45	34.4	2.91	0.20	3.00	7.10	0.29	2.90	3.88	3.45
4.35	5.0	0.16	2.46	0.26	1.95	0.59	0.47	1.37	0.28
4.35	7.1	0.20	1.47	0.40	1.92	0.32	0.18	1.20	0.42
4.35	9.5	0.37	0.92	0.25	2.07	0.16	0.31	1.20	0.62
4.35	12.5	0.44	0.45	0.36	2.22	0.18	0.43	1.16	0.69
4.35	16.4	0.53	0.13	0.48	2.47	0.37	0.54	1.18	0.79
4.35	21.7	0.66	0.22	0.63	2.84	0.48	0.67	1.29	0.95
4.35	34.4	0.67	0.69	0.66	3.27	0.86	0.63	1.27	0.96
5.90	5.0	0.44	2.02	0.52	1.16	0.32	0.14	0.77	0.24
5.90	7.1	0.58	0.88	0.76	0.80	0.32	0.37	0.34	0.33
5.90	9.5	0.38	0.41	0.78	0.87	0.37	0.46	0.35	0.29
5.90	12.5	0.22	0.23	0.29	1.13	0.37	0.27	0.46	0.18
5.90	16.4	0.15	0.21	0.19	1.26	0.52	0.17	0.48	0.26
5.90	21.7	0.10	0.49	0.13	1.40	0.75	0.11	0.43	0.20
5.90	34.4	0.11	0.85	0.10	1.78	1.00	0.10	0.46	0.25
7.40	5.0	0.13	2.27	0.17	1.25	0.62	0.34	0.99	0.21
7.40	7.1	0.26	1.16	0.37	0.83	0.16	0.15	0.51	0.24
7.40	9.5	0.23	0.61	0.43	0.75	0.12	0.17	0.36	0.17
7.40	12.5	0.20	0.27	0.50	0.80	0.25	0.26	0.34	0.25
7.40	16.4	0.22	0.22	0.22	0.87	0.38	0.20	0.33	0.32
7.40	21.7	0.16	0.34	0.21	0.95	0.58	0.19	0.27	0.23
7.40	34.4	0.14	0.65	0.17	1.24	0.78	0.16	0.31	0.22
average	difference	0.75	0.99	0.83	2.67	0.51	0.79	1.43	0.94

conductor loss [25] resulting from the small ratio of metal line thickness to skin depth, t/δ, at low frequencies. Over the reported frequency range, the variation in ϵ_{eff} is as large as 26% for the TFMS on the thinnest polyimide and 12% for the TFMS on the 7.4 μm thick polyimide. The large effect of the conductor loss on ϵ_{eff} makes it impossible to deduce ϵ_{re} which is defined for a loss-less transmission line. Once the ratio of t/δ is sufficiently large, several factors cause TFMS to have very low dispersion: ϵ_r is low, the conductor loss introduces an opposite frequency dependence as the filling factor [17], and the cutoff frequency of the surface wave modes is very high because both H and ϵ_r are small. It is also seen in Fig. 4 that ϵ_{eff} decreases as the polyimide thickness increases and the line width decreases. This last observation is in agreement with the expected results for conventional microstrip [11].

IV. Design Equations

An accurate prediction of the propagation characteristics of the TFMS is required for designing circuits and interconnects, and although many design equations have been reported for conventional microstrip, these have not been verified to be reliable for TFMS design. Therefore, in this work, the reported design equations are compared to the measured propagation characteristics of TFMS. For calculating α and ϵ_{eff} based on the closed form equations from the literature, ϵ_{re} and the characteristic impedance for the loss-less case are derived from [11], ϵ_{eff} is derived from [12], and α_d is given in (1).

To compare the measured attenuation to the attenuation predicted using closed form equations in [5], [14]–[21], the mean difference, $|\alpha_{\text{meas}}(f) - \alpha_{\text{calc}}(f)|$, across the frequency range of 1 to 110 GHz is calculated for each TFMS line

$$\text{mean difference} = \frac{\sum_{i=1}^{N} |\alpha_{\text{meas}}(f_i) - \alpha_{\text{calc}}(f_i)|}{N} \tag{4}$$

where $N = 403$ is the number of frequency points. A summary of these results are given in Table I. Also shown in Table I is the average mean difference for all of the TFMS geometries characterized in this paper. As seen in Table I, the equations in [19] yield the best prediction for conductor loss with an average difference of 0.51 dB/cm for all of the geometries over 1–110 GHz. Lee's [19] equations compensate for the thin metal yielding a better match at low frequency than those that do not [14]–[18]. For Lee's equations, the average error, $|\alpha_{\text{meas}}(f) - \alpha_{\text{calc}}(f)|/\alpha_{\text{meas}}(f)$, across the 1–110 GHz band for the 28 different TFMS lines is between 3 and 21%.

For conventional microstrip with small losses, the effective permittivity increases from ϵ_{re} to ϵ_r as the frequency increases from 0 to ∞, but as shown in Fig. 4, this is not the case for TFMS. The internal inductance of the strip significantly lowers the phase velocity which is interpreted as an increase in ϵ_{eff}. Therefore, the equations used for loss-less microstrip are not adequate for predicting ϵ_{eff} of TFMS and can lead to predicted values of ϵ_{eff} that are too low by 18% when $t/\delta < 1$ and 5%

too low at higher frequencies. If the internal inductance due to the lossy strip is accounted for in the determination of ϵ_{eff}, an equation for the effective permittivity of the lossy line is found to be [25]

$$\epsilon_{\text{eff}}^{L} = \epsilon_{\text{eff}}^{NL} + \frac{cL_i\sqrt{\epsilon_{\text{eff}}^{NL}}}{Z_c^{NL}} \tag{5}$$

where $\epsilon_{\text{eff}}^{L}$ and $\epsilon_{\text{eff}}^{NL}$ are the effective permittivity with and without loss respectively, c is the velocity of light, and Z_c^{NL} is the characteristic impedance of the TFMS assuming no loss. The internal inductance, L_i, is assumed to be small and can be found using equations given by Lee [19]. Equation (5) predicts the correct slow wave effect and reduces the error for low frequencies to 9% and to 1% when $t/\delta \gg 1$.

V. Conclusion

This paper has presented an in depth experimental characterization of thin film microstrip lines on polyimide substrates. It has been shown that the conductor loss for the TFMS is much greater than the dielectric loss. It has also been found that the loss tangent of the Du Pont PI-2611 polyimide is approximately 0.006 in the frequency range of 1–110 GHz. By comparing measured propagation characteristics to design equations for conventional microstrip, it has been shown that equations for conventional microstrip can be used if the effects of having a thin metal strip are accounted for, and in particular, the equations given by Lee [19] give the best accuracy for determining α.

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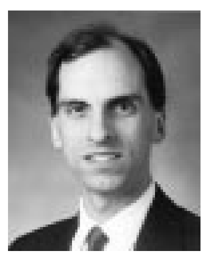

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